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# Recent Progress in the Development of Diesel Surrogate Fuels

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## ABSTRACT

There has been much recent progress in the area of surrogate fuels for diesel. In the last few years, experiments and modeling have been performed on higher molecular weight components of relevance to diesel fuel such as n-hexadecane (n-cetane) and 2,2,4,4,6,8,8-heptamethylnonane (iso-cetane). Chemical kinetic models have been developed for all the n-alkanes up to 16 carbon atoms. Also, there has been much experimental and modeling work on lower molecular weight surrogate components such as n-decane and do-decane which are most relevant to jet fuel surrogates, but are also relevant to diesel surrogates where simulation of the full boiling point range is desired. For the cycloalkanes, experimental work on decalin and tetralin recently has been published. For multi-component surrogate fuel mixtures, recent work on modeling of these mixtures and comparisons to real diesel fuel is reviewed. Detailed chemical kinetic models for surrogate fuels are very large in size. Significant progress also has been made in improving the mechanism reduction tools that are needed to make these large models practicable in multi-dimensional reacting flow simulations of diesel combustion. Nevertheless, major research gaps remain. In the case of iso-alkanes, there are experiments and modeling work on only one of relevance to diesel: iso-cetane. Also, the iso-alkanes in diesel are lightly branched and no detailed chemical kinetic models or experimental investigations are available for such compounds. More components are needed to fill out the iso-alkane boiling point range. For the aromatic class of compounds, there has been no new work for compounds in the boiling point range of diesel. Most of the new work has been on alkyl aromatics that are of the range C7 to C8, below the C10 to C20 range that is needed. For the chemical class of cycloalkanes, experiments and modeling on higher molecular weight components are warranted. Finally for multi-component surrogates needed to treat real diesel, the inclusion of higher molecular weight components is needed in models and experimental investigations.

## INTRODUCTION

Detailed chemical kinetic models are important because they help enable the computational design and optimization of practical devices such as internal combustion engines by enabling simulation of the combustion of transportation fuels like gasoline, diesel, and jet fuels. Development of detailed chemical kinetic models is challenging. Gasoline, diesel and jet fuels derived from conventional petroleum sources are composed of hundreds of compounds. Development of models that represent all these components is prohibitive because the model would be too large for current computational resources. Also, all the fundamental data needed for development of such a model (e.g., chemical kinetic rate constants, reaction paths, thermodynamic parameters) are not available. Thus, simplified “surrogate fuels” are useful for representing current transportation fuels. A surrogate fuel is defined as a fuel composed of a small number of pure compounds whose behavior matches certain characteristics of a target fuel that contains many compounds (e.g., a market diesel fuel). Both the chemical and physical characteristics of the target fuel need to be represented by the surrogate fuel so that the surrogate will properly reproduce not only the combustion characteristics of the fuel, but also the injection,

vaporization, and mixing processes that precede ignition in practical devices. Relevant chemical characteristics of the fuel may include ignition behavior, molecular structures, adiabatic flame temperature, C/H/O content, and sooting propensity. Relevant physical characteristics may include volatility parameters, density, viscosity, surface tension, and diffusion coefficients.

In addition to enabling accurate computational simulations, surrogate fuels are also useful experimentally. First, experimental data on surrogate fuels are needed to validate surrogate fuel models. Second, it is useful to develop surrogate fuels to provide standard fuels whose compositions do not change over time. These standard fuels can be used so that experiments are reproducible. They also allow testing of the same fuel in different experimental devices, geographic locations and using different analysis techniques so that comparisons can be made without fuel variability complicating the results. The compositions of gasoline, diesel and jet fuels vary as the refinery streams and/or other blendstocks from which they are derived change with time. Even if standardized fuels are blended and stored for later use, there is only a finite volume of these standardized fuels available, and they could chemically deteriorate over time. In contrast, surrogate fuels can be reformulated at any time from their constituent pure compounds. Finally, the study of surrogate fuels focuses attention on the fuel properties that are most important for determining engine efficiency, emissions, and other critical performance characteristics. In deciding which properties should be matched between the surrogate and the target fuel, the researcher incorporates hypotheses about the effects of specific fuel properties on mixing, combustion, and other important processes. If the resultant surrogate fuel fails to match the performance of the target fuel adequately, these underlying hypotheses must be reassessed and refined, ultimately leading to an improved understanding of the fundamental relationships between fuel properties and engine performance.

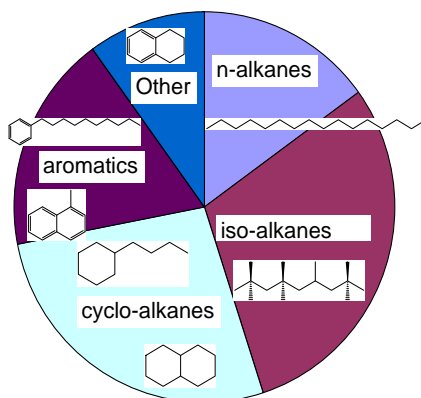
The development of a surrogate fuel model is a lengthy process [1-5]. Chemical kinetic models for each of the pure compounds in the surrogate fuel must be developed and validated by comparison to experimental data. A procedure needs to be identified to choose the relative concentration of each component in the surrogate to best reproduce the properties of the target fuel. The chemical kinetic mechanisms of the individual components need to be combined and important cross reactions between mechanisms included. The surrogate fuel model needs to be reduced in size so that it can be used in multidimensional computational fluid dynamic (CFD) models for simulating engine combustion. Finally, the surrogate fuel model needs to be validated by comparison with surrogate fuel experiments in practical combustion devices of interest.

Physical property models need to be developed for surrogate fuel components and their mixtures. These include models for density, volatility, surface tension, viscosity, thermal conductivity and species transport of the components and their mixtures. Measurements of these properties are also needed for validation of the model. These properties are needed to predict properly the fuel spray break-up, evaporation, and species transport that determine the reacting mixture temperature and species-concentration fields.

In this paper, the current status of diesel fuel surrogate development will be assessed. The review will build on previous reviews of experimental and chemical kinetic modeling of hydrocarbon fuels. In 2003, Simmie [6] reviewed the status of chemical kinetic models and experimental data for the oxidation of hydrocarbon fuels from each of the chemical classes (n-alkanes, iso-alkanes, cycloalkanes, alkenes and aromatics). The progress towards the development of surrogate fuels for diesel was reviewed in the 2007 Farrell et al. paper [1]. Battin-Leclerc [7] recently reviewed in depth the progress in the development of detailed chemical kinetic mechanisms for gasoline and diesel surrogate fuels. The reader is referred to these excellent reviews for relevant work done prior to 2008. The current paper will focus on research progress from 2008 to the present. In the current review, the status of chemical kinetic models of surrogate fuel components, component mixtures and surrogate mixtures will be assessed. Next, chemical kinetic model reduction will be discussed. Finally, progress toward models and measurements of physical properties of surrogate fuels will be examined.

## CHEMICAL KINETIC MODELS FOR DIESEL FUEL COMPONENTS

The relevant components for diesel fuel surrogates have been previously discussed and identified in [1], but they will be reviewed here. The primary chemical classes of the components in diesel fuel are n-alkanes, iso-alkanes, cycloalkanes, and aromatics (Fig. 1). Although the composition of diesel fuel is highly variable, there are some trends [1]: The carbon numbers of the components range from approximately C10 to C22. An average carbon number is 14 or 15. The iso-alkanes are usually lightly branched with one or two side methyl groups. The cycloalkanes typically have one ring with multiple alkyl side chains. There are some two-ring cycloalkanes with alkyl side chains as well. The aromatics are usually one ring with multiple side chains. The average carbon number of the aromatics is about C12 as shown in the composition data in [1]. This carbon number is lower than the other chemical classes. There are also some two-ring aromatics with alkyl side chains.



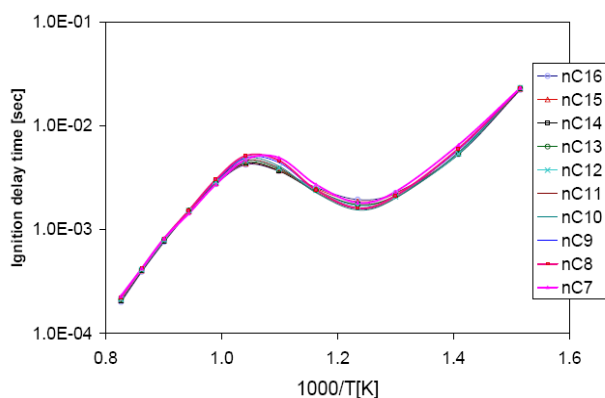
**Figure 1. Relative amounts of various chemical classes in diesel fuel.**



In the following sections, recent developments in chemical kinetic models and experiments for each chemical class will be discussed in turn.

## ***n*-Alkanes**

There has been much recent progress on the development of chemical kinetic models for components relevant to diesel fuel. Most of the progress has been in the chemical class of *n*-alkanes. Chemical kinetic detailed mechanisms for *n*-alkanes from *n*-C8 up to *n*-C16 have been developed [8, 9]. Together with previous work [10, 11], this allows the simulation of all *n*-alkanes up to C16. The mechanisms include low temperature chemistry which is essential for investigating low temperature combustion strategies in diesel engines. Figure 2 shows a simulation of the ignition delay of large *n*-alkanes at 13 bar from low to high temperature [5]. The model predicts that all *n*-alkanes from *n*-C7 to *n*-C16 ignite with nearly the same ignition delay times within a factor of about 1.5. This trend was not seen in the simulations of [9], but was seen in the shock tube experiments of [12] discussed later. For C10 and C12 *n*-alkanes, there has been considerable progress reported in the literature. You et al. [13] developed a mechanism for *n*-dodecane and *n*-decane that is valid above 850K. It was validated by comparison to pyrolysis experiments in plug flow and jet stirred reactors, and by comparison to shock-tube ignition delay times and laminar flame speeds. This model has been further improved and validated, and is available at [14]. In other work, Zhang et al. [15-18] extended a high-temperature, *n*-heptane mechanism up to *n*-hexadecane with a focus on predicting the formation of the unsaturated soot-precursor species in premixed flames.



**Figure 2. Ignition behavior of a series of large *n*-alkanes (stoichiometric, fuel-air mixtures, initial pressure of 13.5 bar) [8].**

There also been considerable progress in acquiring experimental data for large *n*-alkanes. These experimental data are valuable for validating detailed chemical kinetic mechanisms and for gaining insight into the behavior of these fuels. Shen et al. [12] have recently obtained shock tube ignition data for a series of large *n*-alkanes up to C16. Their experiments were performed over a temperature range of 786-1396K, a pressure range of 9-58 atm and for equivalence ratios of 0.25, 0.5, and 1.0. These conditions of pressure and temperature simulate conditions found in

internal combustion engines. Experimental results in Figure 3 show that the measured ignition delay times are very similar for a series of large n-alkanes. The curves that encompass the data give about a factor of two variation in ignition delay times compared to a factor of 1.5 seen in the Westbrook et al. simulations (Fig. 20) and indicate a general trend for large n-alkanes. However, the experimental work does not cover the complete low temperature regime from 650-780K. In other work, Biet et al. [9] obtained experimental data for n-decane and an n-hexadecane/n-decane mixture in a jet stirred reactor at 1 atm over a range of temperatures from 550-1100K. Their detailed chemical kinetic model was able to reasonably reproduce their experimental data. In a subsequent paper on the same fuel mixture, Hakka et al. [19] were able to identify a much more complete spectrum of intermediate species including high-molecular weight alkenes, aldehydes, ketones and cyclic ethers in the jet stirred reactor.

Significant experimental validation data has recently become available in the lower molecular weight range of diesel (C10 and C12 n-alkanes) because this carbon range is also important for jet surrogate fuels, which have received considerable recent attention. Vasu et al. [20] measured shock tube ignition delay times and OH concentration histories for n-dodecane. Their experiments were performed over a temperature range of 727-1422K, a pressure range of 15-34 atm and for equivalence ratios of 0.5 and 1.0. Their experimental data for ignition delay times agree quite well with Shen et al. [12].

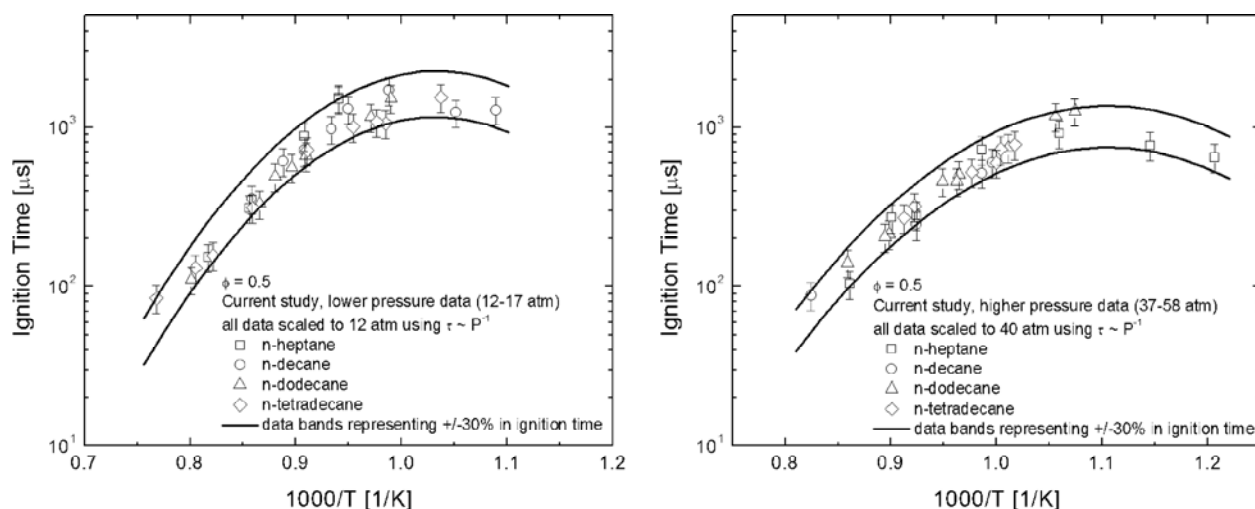
The shock tube studies above considered equivalence ratios up to 1. There is a need to investigate equivalence ratios greater than 1.0 because diesel engine ignition occurs at equivalence ratios of about 2-4 under conventional diesel engine conditions [21]. This equivalence ratio range should be extended to the low end (about  $\phi=0.3$ ) to explore new strategies of low temperature combustion in a diesel engine [22, 23]. Thus, a range of equivalence ratios from approximately 0.3 to 3 is needed for fundamental validation data relevant to diesel engine conditions. Such fuel-rich conditions may be challenging in a heated shock tube where adequate vaporization is difficult to achieve with high molecular weight fuels.

Davidson et al. [24] examined n-dodecane in their aerosol shock tube, which allows the investigation of ignition of high boiling point fuels without heating the shock tube. Although their experiments were at lower pressures (5.8 -6.7 atm) than other studies, they found similar trends for ignition delay with temperature as Vasu et al. when the usual  $P^{-1}$  pressure dependence was assumed. Zhukov et al. [25] examined the shock tube ignition of n-decane at high pressures up to 80 atm and temperatures ranging from 800-1300K for stoichiometric and lean mixtures. The above experimental data were all taken at conditions relevant to internal combustion engines.

Kumar et al. [26] studied the ignition of n-decane in a rapid compression machine (RCM) at compressed-gas pressures of 7-30 bar, compressed gas temperatures of 635-770K and equivalence ratios of 0.5 to 2.2. They found two-stage ignition behavior over the entire range of conditions that they investigated. Their measured ignition delay times agree with the shock tube

ignition delay measurements of Pfahl et al. [27] at an equivalence ratio of 0.5, but are shorter than Pfahl et al. at near stoichiometric conditions. Discrepancies were identified between Kumar et al.'s measured ignition delay times and the predictions of two chemical kinetic models [8, 28]. Kumar et al. [29] also measured the laminar flame speeds of n-decane and n-dodecane in a counterflow configuration at unburned reactant temperatures of 360-470K, equivalence ratio range of 0.7-1.4 and atmospheric conditions. Biet et al. [9] improved the automatic generation of a chemical kinetic mechanism for n-alkanes by improving the treatment of the consumption of primary products such as alkenes, aldehydes and cyclic ethers. They applied the mechanism to the simulation of their new experimental data for stoichiometric mixtures of n-decane and n-decane/n-hexadecane in a jet stirred reactor at 1 atm over a temperature range of 550 to 1100K. They also used the new chemical kinetic mechanism to simulate the experimental data of n-decane in a perfectly stirred reactor by Dagaut et al. [30] and n-dodecane in a flow reactor [31]. The agreement between the new chemical kinetic mechanism and measurements for the different experimental configurations and n-alkanes was reasonable. In a later study, Hakka et al. [19] measured a more complete set of intermediate products for n-decane and an n-decane/n-hexadecane mixture in a jet stirred reactor at the same conditions.

For n-alkanes, more experimental data are needed to fill out the carbon range from C15 to C20. However, for these higher molecular weight fuels, it is difficult keep the compounds in the vapor phase in fundamental experimental devices. More experimental data are now available for large n-alkanes. These additional data should be used to help further validate and develop chemical kinetic models. An additional need is for experimental validation data that includes species typical in engines when exhaust gas recirculation (EGR) is employed. These species are water, carbon dioxide, carbon monoxide, nitric oxide, molecular nitrogen and others. A recent paper [32] has identified discrepancies between chemical kinetic model predictions and experimental measurements when EGR is included. The work focused on the effects of the EGR species water, carbon dioxide, and molecular nitrogen.



**Figure 3.** Experimentally measured ignition delay times for C7, C10, C12 and C14 n-alkanes at an equivalence ratio of 0.5 [12]. Reprinted (“Adapted” or “in part”) with permission from [12]. Copyright 2009 American Chemical Society.

### *iso-Alkanes*

There has been significant progress in the area of iso-alkanes, particularly for iso-cetane (2,2,4,4,6,8,8-heptamethylnonane), a primary reference fuel for diesel engines. Oehlschlaeger et al. [33] measured shock tube ignition delay times for iso-cetane at conditions relevant to diesel engines (temperatures from 953-1347K, pressures from 8-47 atm and for equivalence ratios of 0.5, 1.0 and 1.5). These measurements were compared to a newly developed chemical kinetic mechanism for iso-cetane based on a previous and successful model for iso-octane [34]. The computed and measured results showed good agreement. A similarity was found between the autoignition process of iso-cetane and iso-octane. The low reactivity of both fuels at these intermediate to high temperatures can be attributed to the production of iso-butene which produces relatively stable 2-methyl-allyl radicals.

Dagaut et al. [35] investigated the oxidation of iso-cetane/O<sub>2</sub>/N<sub>2</sub> mixtures in a jet stirred reactor at 10 atm and equivalence ratios of 0.5, 1.0 and 1.5. They measured the species concentrations in the reactor over a temperature range from 770-1070K. Their results showed iso-butene as the major hydrocarbon intermediate. They simulated their results with two chemical kinetic models. One had lumped chemistry for the whole scheme [36]. The other used automatic generation to produce the mechanism [37]. It had detailed chemistry for the fuel, C0 and C1 species, with lumped chemistry for the remaining reactions. Neither detailed model included low temperature chemistry since none was observed with the highly-diluted mixtures used. The fully lumped model [36] was unable to satisfactorily reproduce the experimental data. The partially lumped model [37] simulated the fuel profiles very well, but predicted ethene instead of iso-butene as the major hydrocarbon intermediate.

There is still a considerable gap in knowledge for large iso-alkanes, particularly lightly-branched iso-alkanes that are more representative of diesel fuel components. Inclusion of these additional iso-alkanes would offer a more diverse palette for choosing components to represent diesel fuels. With regard to physical properties, experimental and modeling characterization of a series of iso-alkanes may be helpful to properly represent the distillation curve of diesel fuel. Huber et al. [38] have found that iso-alkanes need to be included in a surrogate to properly simulate the thermal conductivity of liquid diesel fuel.

## ***Cycloalkanes***

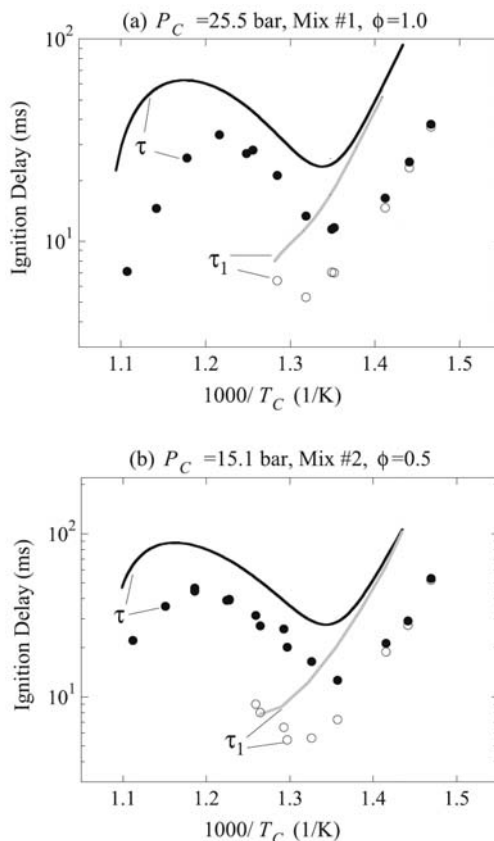
Cycloalkanes usually comprise less than 5% of diesel fuel derived from conventional crude-oil sources [1], but are much higher in alternative diesel fuel derived from oil-sands deposits [39]. The cycloalkanes in diesel usually have multiple, alkyl side chains [1]. Discussed below is recent progress in chemical kinetic models and experimental data, starting with C6 cycloalkanes and increasing in carbon number.

There has been considerable progress on the development of chemical kinetic models for cyclohexane. Detailed chemical kinetic models for the oxidation of cyclohexane have been developed [40-42]. These models generally reproduce well the oxidation of cyclohexane under conditions in a stirred reactor and rapid compression machines [43, 44]. In other work, Zhang et al. [45] developed a chemical kinetic model for cyclohexane and compared their model predictions to experimentally measured intermediate products in a low-pressure, premixed flame [46]. They focused on the pathways that lead to benzene formation.

Recently, a more accurate description of important low temperature reactions for cyclohexane oxidation has become available [47]. These reactions involve the addition of molecular oxygen to cyclohexyl radicals and subsequent isomerization reactions including the temperature and pressure dependence of their rate constants. This new knowledge of the complex behavior of these rate constants will likely allow a more accurate description of the ignition behavior of cyclohexane over the wide temperature and pressure range found in a diesel engine.

Much new experimental data on cyclohexanes has recently become available. Mittal and Sung [48] investigated the ignition of methylcyclohexane in an RCM at equivalence ratios of 0.5, 1.0 and 1.5, pressures of 15 and 25 bar and over a compressed-gas temperature range of 680-905K. The chemical kinetic model of Pitz et al. [49] predicted the shape of the measured ignition times with temperature, but the predicted times were longer than the measured times (Fig. 4). A two-stage ignition with a strong negative coefficient behavior was observed where the ignition delay increases with increasing temperature. Yang and Boehman [50] have studied the oxidation of cyclohexane and methylcyclohexane under motored engine conditions. They measured the concentration of intermediate products including cyclic ethers that are an indication of low temperature chemistry. They showed that a methyl group side chain on the ring (i.e., methylcyclohexane) enhances the reactivity of the fuel. Vasu et al. [51, 52] measured the

ignition delay times of methylcyclohexane over a wide range of temperature and pressure (800-1550K, 1-50 atm, and  $\phi = 0.5$ -2.0). They also measured OH concentration histories to provide further validation targets for chemical kinetic models. The same Stanford research group [53] also investigated the shock tube ignition of cyclohexane and cyclopentane over a range of conditions important for internal combustion engines (11-61 atm, 847-1379 K, and equivalence ratios of  $\phi = 1.0$ , 0.5, and 0.25). They found that current models [40, 41] captured the general trends of their experimental data, but their predicted ignition delays were generally longer than those measured.



**Figure 4. Comparison of experimental (symbols) and computed (lines) ignition delays of methylcyclohexane for (a) compressed gas pressure,  $P_C = 25.5$  bar, Mix #1 ( $O_2/N_2/Ar = 10.5/12.25/71.75$  ( $\phi = 1.0$ ) and (b)  $P_C = 15.1$  bar, Mix #2 ( $O_2/N_2/Ar = 7.16/16.35/71.75$ ) ( $\phi = 0.5$ ) [48].**

Vanderover and Oehlschlaeger [54] investigated the shock tube ignition of methylcyclohexane and ethylcyclohexane over wide range of conditions (881-1319K, 11-70atm,  $\phi = 0.25$ , 0.5, 1.0). Their results showed the predicted ignition delay times from a recent chemical kinetic model [49] were too long at high pressure (50 atm). Sivaramakrishnan and Michael [55] experimentally measured rate constants for OH radicals with cyclohexane and methylcyclopentane. These rate constants will allow a more accurate description of the consumption reactions for cycloalkanes. In other work, Ciajolo et al. [56] measured the

intermediate products of cyclohexane in a rich premixed flame and compared the results to their lumped chemical kinetic mechanism for cyclohexane. They found good agreement between the experimental and predicted profiles. They also added a soot model to the mechanism, but were not able to predict the early soot formation observed with cyclohexane. Bieleveld et al. [57] measured the autoignition temperatures and extinction conditions for methylcyclohexane. They found its ignition and extinction behavior to be between that of n-heptane and iso-octane.

For two-ring cycloalkanes, Oehlschlaeger et al. [58] measured the ignition delay times for a mixture of *cis*- and *trans*- decalin over a wide range of conditions (990-1300K, 9-15 atm and 35-48 atm, equivalence ratios of 0.5 and 1.0). They generated a lumped mechanism for decalin that contained high temperature chemistry only. The predicted ignition delay times compared reasonably well with the measured times. Yang and Boehman [59] investigated the oxidation of decalin (mixture of 62% of *trans*- and 38% *cis*- isomers) in a CFR octane-rating engine operated under motored engine conditions. They measured products in the exhaust of the engine at an engine speed of 600 rev/min, equivalence ratio of 0.25, intake temperature of 200°C and a compression ratio range of 4.5 to 12.2. Decalin exhibited significant low-temperature heat release in their motored engine. It reacted to aldehydes, small alkenes and CO through low temperature paths. Decalin also dehydrogenated to form hydronaphthalenes, naphthalene and decalin. It underwent ring opening reactions. In other work, Chae and Violi [60] computed rate constants for the decomposition of decalin using density functional theory.

Although much progress has been made on cycloalkanes, more work is needed to cover the full carbon range of cycloalkanes. Single ring compounds, (C6 and C7 cycloalkanes) have been examined well. For C8 and C9, there is one study each [54] and [61], respectively. To our knowledge, there are no data available for one-ring cycloalkanes larger than C9. However, the full diesel range for cycloalkanes extends up to about C22 with an average of C14 or C15 [1]. Thus, there is a need to examine higher molecular weight compounds. These studies are challenging because fundamental investigations usually require maintaining these high boiling point compounds in the gas phase. Also, there is limited availability of such compounds at a reasonable price, even for relatively small quantities needed in fundamental combustion experiments.

## ***Aromatics***

Aromatics comprise a large fraction of diesel (about 30-35% by weight on average) [1]. Most of these aromatics are 1-ring with alkyl substitutions [1]. In the following section, developments in the chemical kinetic modeling and experimental investigation of alkyl substituted benzenes are discussed. (Benzene is not included because it is not present at any significant level in diesel fuel.)

There has been much progress in the development of chemical kinetic mechanisms for the only C7 aromatic, toluene. Sakai et al. [62] made many improvements in the treatment of different

reaction classes in toluene. They compared computed ignition delay times to those experimentally measured in a shock tube [63, 64]. Mehl et al. [65, 66] made further improvements to the Sakai et al. mechanism. They were able to simulate well the experimentally measured ignition delay times of Mittal et al. [67] in a rapid compression machine and Shen et al. in a shock tube [68]. The simulations showed that the discrepancies between ignition delay times in the shock tube and rapid compression machine could be explained by heat losses in the RCM. The Shen et al. [68] shock tube experiments covered a wide range of conditions (1021-1400 K, pressures of 10-61 atm, and equivalence ratios of 1.0, 0.5, and 0.25.) They did not observe early pressure rise during the ignition process for toluene reported by Davidson et al. [69], nor did the Mehl et al. model predict such pressure rise. Blanquart et al. [70] extended their chemical kinetic mechanism to include toluene. They obtained good agreement between predicted and measured shock tube ignition delay times at high temperature and laminar flame speeds at 1 atm.

Shen et al. [71] studied the autoignition of the C8 aromatics (ortho-xylene, meta-xylene, para-xylene and ethylbenzene) in a shock tube over a wide range of conditions relevant to diesel engines (941-1408 K, 9-45 atm, and equivalence ratios of 5.0 and 1.0). Ethyl benzene was found to be the most reactive followed by the less reactive xylenes, ortho, meta and para. Ignition delay times for p-xylene matched up closely with their recent toluene measurements [68].

Roubaud et al. [72, 73] studied C9 aromatics in a RCM at compressed gas temperatures of 600 to 900K and pressures of 12-15 atm. They examined the ignition of 1,2,3-trimethyl benzene, 1,2,4-trimethyl benzene, 1,3,5-trimethyl benzene and 2-ethyl toluene in stoichiometric, O<sub>2</sub>-inert mixtures. They found that 1,2,3-trimethyl benzene, 1,2,4-trimethyl benzene, and 2-ethyl-toluene ignited more easily than 1,3,5-trimethyl benzene. They attributed the easier ignition to the availability of ortho alkyl groups with their more easily transferable H-atoms in the alkylbenzylperoxy radicals formed by these C9 aromatics. These internal H-atom transfers lead to chain branching and higher reactivity. Trimethylbenzenes were also studied in other work in binary mixtures with 1-methylnaphthalene discussed below.

For C10 aromatics, Pousse et al. [74] developed a high temperature mechanism for n-butylbenzene. They compared computed results with experimental measurements of species concentrations from a low-pressure, lean, premixed, methane flame doped with n-butylbenzene and obtained satisfactory agreement.

## ***Naphthalenes***

There has not been a great deal of recent progress on naphthalenes. Mati et al. [75] measured the species concentrations for 1-methylnaphthalene oxidation in a (JSR) at 800-1421K, 1-10 atm and at  $\phi=0.5-1.5$ . They developed a chemical kinetic mechanism for 1-methylnaphthalene and compared the computed results to their JSR measurements and the shock tube ignition measurements of Pfahl et al. [27]. Bounaceur et al. [76] developed a chemical kinetic



mechanism for 1-methylnaphthalene and validated it by comparison to experiments in a shock tube (900-1500K, 13 bar, stoichiometric) [77], flow reactor (1170K, 1 atm,  $\phi=0.6, 1.0, 1.5$ ) [78], and jet stirred reactor (800-1100K, 10 bar, stoichiometric mixtures). There is a need to obtain more experimental data on ignition delays for alkyl substituted naphthalenes in shock tubes and RCMs at conditions relevant to diesel engines (800-1200K, 10-50 atm,  $\phi=0.5-3$ ). A lower limit temperature of 800K is listed here because these compounds will probably not ignite on the time scale of milliseconds below 860K, based on the experimental data of Pfahl et al. [27].

### ***Tetrahydronaphthalenes***

Yang and Boehman [59] investigated the oxidation of tetralin in a CFR octane-rating engine operated under motored engine conditions. They measured the products in the exhaust of the engine at an engine speed of 600 rev/min, equivalence ratio of 0.25, intake temperature of 200 C and a compression ratio range of 4.5 to 12.2. Unlike the previously discussed decalin, tetralin exhibited little low temperature chemistry in their motored engine. Tetralin mainly dehydrogenated to form 1,2-dihydronaphthalene and naphthalene. Ring-opening reactions occur to a much less extent for tetralin compared to decalin. No additional information could be found on the oxidation of tetrahydronaphthalenes in the peer-reviewed literature. However in his Ph.D. thesis, Wilk [79] studied the oxidation of mixtures of n-dodecane and tetralin (tetrahydronaphthalene) in a constant volume vessel at 60 to 240 torr and 520-620K. He added 5, 10 and 20% tetralin to n-dodecane. He found the addition of tetralin to n-dodecane increased the pressure where the onset of cool flames is observed for temperatures below 530K. Above 530K, the addition of tetralin has little effect on the pressure where the onset of cool flames is seen. He also found that the addition of tetralin increased the induction period before cool flames are observed. This effect was nonlinear with the 5% addition of tetralin having the largest effect and subsequent addition of tetralin having proportionally smaller effect.

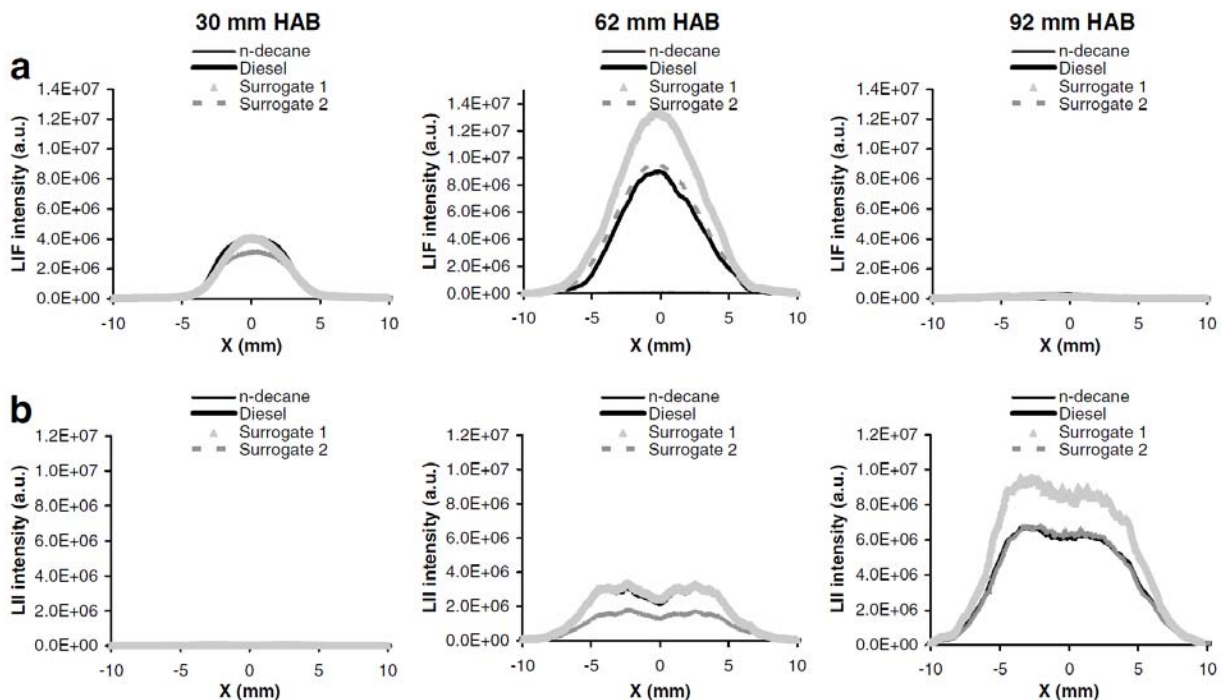
### **SURROGATE MIXTURES**

Surrogate mixtures are mixtures of components used to represent the target, real fuel whose behavior one desires to model. The behavior of multicomponent fuels is more complicated than single component fuels because species produced from one component can react with species from another component. These interactions often manifest themselves in the observed ignition delay times, flame speeds and other combustion characteristics of surrogate mixtures. The interactions need to be quantified by experiments and correctly simulated by chemical kinetic models so that combustion behavior of practical fuels can be accurately predicted. In the discussion below, recent research on surrogate mixtures is reviewed starting with binary mixtures and then progressing to more complex mixtures.

Honnet et al. [80] investigated the Aachen surrogate of 80% n-decane and 20% 1,2,4-trimethylbenzene used to represent JP-8 jet fuel. They performed experiments in a laminar, counterflow, diffusion-flame. They found that the Aachen surrogate had similar ignition and

extinction characteristics, and measured soot concentrations compared to JP-8 in the counterflow flame. They developed a detailed chemical kinetic model to describe the Aachen surrogate and validated it over a wide range of conditions. The predictions of the chemical kinetic model compared fairly well with their experimental measurements of ignition and extinction.

Lemaire et al. [81] have investigated the IDEA surrogate diesel fuel [82] which consists of 70% n-decane and 30% 1-methyl naphthalene (1-MN) and compared it to a low-sulfur diesel that contained 8% by volume esters. They investigated these fuels in an atmospheric pressure, flat flame burner with an injector tube in the center that nebulizes the liquid fuel and produces an aerosol. The flat flame burner is supplied with methane-air mixture. Based on laser induced incandescence (LII) of the soot and laser induced fluorescence of the PAH (polycyclic aromatic hydrocarbons desorbed from the soot), they found that the IDEA fuel produced too much soot and PAHs compared to the low sulfur diesel fuel. Therefore, they reduced the amount of 1-MN in the surrogate fuel. To determine the amount of 1-MN, they used the threshold soot index (TSI) and matched the TSI of the surrogate and the diesel fuel. A surrogate with 20% 1-MN (instead of previously used 30%) matched the TSI of the diesel fuel. This new surrogate also matched the measured LII and PAH levels of the diesel fuel quite well (Fig. 5). This work supports the use of TSI to match the sooting behavior of the surrogate with the target real fuel [83-85], but it is not clear that fuel-induced changes in TSI quantitatively indicate the magnitude of fuel-induced changes in exhaust particulate matter (PM), soot, or smoke emissions from a diesel engine. When the researchers examined the PAHs absorbed on the soot, they found that the molecular weight distribution of the measured PAHs from the surrogate was more narrow compared to that from the diesel. Also note that the oxygenate content of the ester components in the low sulfur fuel likely reduced the level of soot and PAH below that of produces by a conventional diesel. This means that although the new surrogate works best compared to this diesel containing esters, the standard IDEA surrogate with 30% 1-MN may still work best in comparison to conventional diesel fuel. However, the findings of this work concerning how to match a surrogate fuel to a target real fuel are important.



**Figure 5. Radial profiles of (a) laser-induced fluorescence of PAH and (b) laser-induced incandescence (LII) of soot particles obtained at different heights above the burner (HAB) in each flame. Surrogate 1 is original IDEA fuel of 30% 1-MN/70% n-decane. Surrogate 2 is new proposed surrogate of 20% 1-MN/80% n-decane. N-decane signals are very weak indicating near zero soot on this plot. The triangles and dashed line sometimes appear as solid lines [81].**

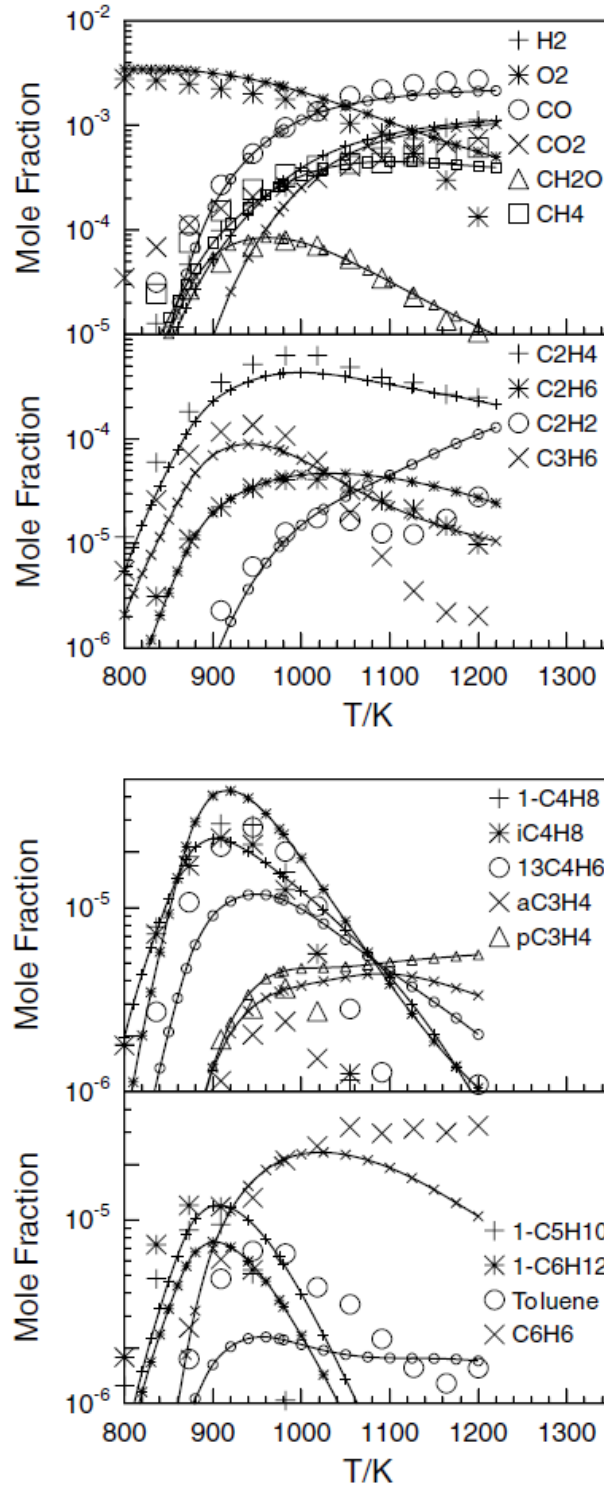
Kook and Pickett [86] investigated a surrogate of 23% m-xylene and 77% n-dodecane and compared it to a conventional jet fuel in a high-pressure, high-temperature combustion vessel used to simulate conditions in a diesel engine. Using planar laser-induced incandescence (LII), they showed that the surrogate fuel sooted more than the conventional jet fuel in the diesel engine. They attributed this behavior to the surrogate fuel having a higher aromatic content than conventional jet fuel. Natelson et al. [87] tested the reactivity of a surrogate containing 50% n-decane / 25% n-butylbenzene / 25% n-butylcyclohexane in a pressurized flow reactor at 8 bar. This surrogate matches the maximum aromatic content allowed in jet fuel and the H/C ratio in a US average JP-8 jet fuel [3]. They also tested a surrogate containing 33% n-decane / 33% n-butylbenzene / 33% n-butylcyclohexane which was proposed to match diesel fuel properties. They used the amount of CO formation in the flow reactor as a measure of reactivity of the surrogate and the target fuels. They found these surrogates to be more reactive than the jet and diesel fuels they were designed to match.

Steil et al. [88] found that modeling predictions for a surrogate mixture of 70 % n-decane / 30 % propylbenzene did not well represent experiments on shock tube ignition of kerosene.

Mati et al. [89] compared computed results of a five component mixture model with experimental measurements using a blended, synthetic diesel fuel in a jet stirred reactor (JSR)

( $T = 800\text{--}1400\text{K}$ ,  $\phi = 0.5 - 2$ ,  $P = 1$  and  $10$  atm). In the experiments, gas samples were extracted from the JSR with a fused silica probe and analyzed online and offline by gas chromatography with a flame ionization detector and mass spectrography. Species profiles of some of the measured species are shown in Fig. 6. The amounts of the five components (23.5% n-hexadecane, 19% iso-octane, 26.9% n-propylcyclohexane, 22.9% n-propylbenzene and 7.7% 1-methylnaphthalene) used in the chemical kinetic model were chosen to match the amount of the various chemical classes in the synthetic diesel fuel (n-alkanes, iso-alkanes, cyclo-alkanes, alkyl benzenes and two-ring aromatics). The reactivity of the synthetic diesel fuel, based on the CO and O<sub>2</sub> profiles, was well reproduced by the surrogate model at 10 atm for the stoichiometric and fuel-rich case (Fig. 6), but not at 1 atm. The comparison of the predicted and measured intermediate species profiles in the JSR was similarly much better at 10 atm than at 1 atm. For the best comparisons (e.g., Fig. 6), the surrogate model was able to reasonably match many hydrocarbon intermediates and CO, but not CO<sub>2</sub>. Because of poor agreement at 1 atm, further work needs to be done to investigate the effect of pressure in the experimental results and model simulations. The comparison of the experimental and modeling results seems to substantiate that CO is a good measure of agreement in fuel reactivity between the model and experiment. This is the same method of measuring fuel reactivity used by the Drexel group in their high-pressure flow reactor [87]. When the comparison between the experimental and predicted CO was poor, the agreement of the rest of the species profiles was generally poor.

Myong et al. [90] experimentally investigated the injection of a diesel surrogate into a constant volume vessel filled with argon at a temperature of 400-700K and a density of 5-20 kg/m<sup>3</sup>. A common rail fuel injector was used. They found the high-boiling point component the diesel surrogate controls liquid phase length of the evaporating spray. In a later paper [91], they found that evaporation of the surrogate fuel is promoted by addition of a low boiling point component because the saturated-vapor pressure line of the high boiling point component shifts to a lower temperature in the two-phase region.



**Figure 6.** Comparison of a surrogate diesel model and synthetic diesel fuel experiments in a jet stirred reactor at 10 atm and  $\phi = 2$  (diesel, 0.05%; O<sub>2</sub>, 0.345%; N<sub>2</sub>, 99.6%; residence time = 0.5 s) [89].

In future work on surrogate fuels for diesel, surrogates need to be investigated that contain components that are more representative of the carbon range in diesel fuel (C10 to C22) [1].

There is a lack of representative components on the high end of the carbon range. Also, iso-alkanes need to be added to the surrogate in the appropriate carbon range.

## **REDUCTION OF DETAILED CHEMICAL KINETIC MECHANISMS**

There are many ways to reduce the computational costs of including fuel chemistry in reacting flow models. The most obvious way is to reduce the number of species and reactions in the mechanism, while maintaining the accuracy required for a given application [92, 93]. This reduction can be done by creating skeletal mechanisms and by lumping of species [94]. Skeletal mechanisms can be formed by a variety of methods including directed relational graph [95] and reaction flow analysis [96]. Further computational gains can be made by accounting for species that are in steady state [97] or partial equilibrium. An alternative to reducing the size of the detailed mechanism is to save computational time by pre-calculating the chemistry and using table lookups [98]. Mechanism reduction can be done “on the fly” during a reacting flow calculation, so that much smaller mechanisms can be used at different times and locations on the computational grid [99, 100]. There are other ways to reduce computational times. The computational efficiency of chemistry solvers can be improved [101]. The chemistry can be solved on a coarser computational grid than the flow dynamics, as is done in multizone HCCI calculations, which resulted in large computational speed-ups [102]. These methods and others have been reviewed recently by Lu and Law [103].

There has been much recent work on how to reduce chemical kinetic mechanisms and their associated computational costs. Lu and Law and co-workers have a series of papers on the directed-relational graph (DRG) method for mechanism reduction and stiffness removal for further computational cost reduction [103-105]. After performing DRG, lumping, quasi steady-state analysis (QSSA) and stiffness removal, they reduced a 561-species and 2539-reaction n-heptane mechanism [10] to 52 species and 48 global reactions, while maintaining accuracy on target calculations for extinction in a perfectly-stirred reactor and constant-pressure ignition over a wide range of temperature and pressure [103] (Fig. 7). Prager et al. [106] also reduced Curran et al.’s n-heptane mechanism, but used the method of computational singular perturbation (CSP) [107]. They got good agreement for n-heptane premixed flames over a range of equivalence ratios and pressures. They were able to reduce the n-heptane mechanism to 66 species and 326 reactions. Neimeyer et al. [93] combined the DRG method with sensitivity analysis and error-propagation to reduce an n-decane mechanism of 940 species and 3887 reactions to a skeletal mechanism containing of 211 species and 794 reactions. Pepiot-Desjardins and Pitsch [108] also used the DRG method and developed an approach to reduce a mechanism based on prediction of a series of targets, like ignition delay time, with a user-defined error tolerance. Sun et al. [92] have developed a direct path flux analysis method for generating skeletal mechanisms and found greater accuracy for a similar reduction in number of species than the DRG method over a wide range of pressures and temperatures.

Hughes et al. [97] reduced an n-heptane mechanism of 358 species and 2411 reactions created by EXGAS [37] to a skeletal mechanism. Using QSSA, they further reduced the mechanism to 81 species and 341 reactions while retaining accurate reproduction of low and high temperature chemistry of the detailed reaction mechanism.

Nagy and Turányi [109] have developed an approach where strongly connected sets of species in a detailed mechanism are identified and added to a test mechanism in sequential steps, while checking for errors by comparison with simulations using the fully detailed model. Multiple test mechanisms are developed. The test mechanism with the smallest error and least CPU requirement is selected. They reduced a surrogate fuel mechanism with 345 species and 6874 reactions to 47 species and 246 reactions and obtained a computational speedup of 116 times in a zero-dimensional, methane-air, homogeneous reaction problem.

Oluwole et al. [110] have developed a method that determines the range of validity (pressure, temperature and equivalence ratio) for a given reduced mechanism.

Liang et al. [100] used a dynamic adaptive chemistry strategy to reduce the chemistry “on the fly” in a reacting flow calculation. For a zero-dimensional, single-zone, HCCI engine calculation, they obtained a 70-fold CPU time reduction with a 1099 species mechanism of a gasoline surrogate fuel.

Singer and Green [111] developed an adaptive orthogonal decomposition method to solve the reaction-diffusion equation in reacting flow problems. The method allows a reduction in the number of equations that govern the combustion chemistry. For a one-dimensional, methane-air, premixed, laminar flame, they saw a speedup of 3.5 times in the reacting flow computation using GRIMech 3.0 [112].

It is difficult to determine the best methods to reduce detailed chemical kinetic mechanisms and their associated computational costs. Combined techniques, as promoted by Lu and Law [103], are likely to be a successful approach and used in future work. It is also likely that improvements in the numerical solvers [101, 111] will be combined with mechanism reduction techniques. Techniques such as CSP and principle component analysis may be more useful as tools to interrogate reaction mechanisms and to determine the controlling rate processes [113], than as mechanism reduction tools. For example, Lu et al. [114] used CSP to develop an explosive analysis to interrogate reaction models and identify important species that lead to ignition. Speeding up the chemistry solvers is an ideal way to reduced computational time because it does not require the user to reduce the size of the mechanism. A faster chemistry solver called a sparse matrix solver was recently included in Chemkin [115]. In the long term, “on the fly reduction”, likely will be employed because the reduced mechanisms produced need not be valid over the whole solution domain with this method, leading to greater mechanism reduction and computational speedups. Also “on the fly” methods do not require user time in performing lengthy mechanism reduction calculations.

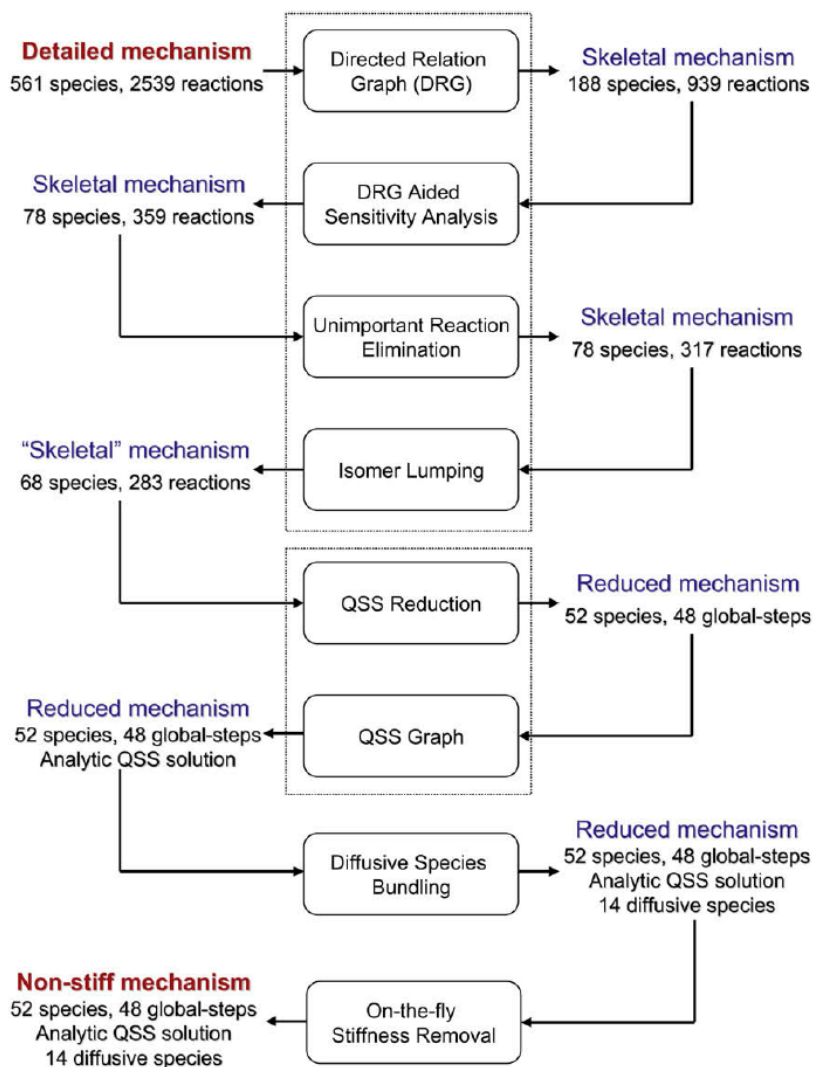


Figure 7. Flow chart of the integrated reduction procedure for an n-heptane mechanism [103].

## SELECTION OF SURROGATE MIXTURES TO REPRESENT DIESEL FUEL

Once a palette of surrogate compounds is available, a procedure is needed to select the surrogate compounds and their amount that will be included in a surrogate fuel. Various procedures have been examined and discussed in the literature [4, 5, 83, 116].

Zhang et al. [116] matched chemical composition of a surrogate fuel to the target practical fuel (JP-8, a common aviation fuel) by using nuclear magnetic resonance (NMR) analysis. They tried to match as closely as possible the relative amounts of each type of carbon atom identified by NMR in the surrogate and the target fuels. The types of carbon atoms identified included those bonded to primary, secondary and tertiary H atoms. Other types of carbon atoms considered were aromatic carbons bonded to an H atom or to a carbon substitute. Carbons attached to



bridges across cyclic compounds were identified, as well as additional types of carbon atoms. Finally, an attempt was made to match the relative amounts of eight types of NMR-classified carbon atoms in the surrogate and the target fuel.

Colket et al. [83] discussed the combustion and physical properties that are important to match between a surrogate fuel and a target practical fuel. In the case of jet fuel, they stated that H/C ratio, amount of each chemical class (e.g. aromatics), heat of combustion, smoke point [84], viscosity and distillation curve were the most important properties to match. Instead of smoke point, threshold sooting index (TSI) [85] and yield sooting index (McEnally and Pfefferle) could alternatively be used for accessing the sooting propensity of the fuel. To match chemical composition, they suggested NMR analysis [116]. They indicated that the above properties can be estimated using the proposed composition of the surrogate. They outlined an approach for making these property estimations.

Dryer et al. [5] presented a method for specifying a surrogate fuel composition for jet fuel. They advocated matching the following properties in the surrogate and the target jet fuel: C/H ratio, threshold sooting index (TSI), and cetane number. They stated that is important to match the C/H ratio because it affects surrogate properties such as flame temperature, heat of reaction, flame speed, and local air/fuel stoichiometric location. In addition, C/H ratio of the surrogate fuel affects the total air/fuel flow rates through a combustion device. They recommend using cetane number to match the ignition properties of the surrogate and jet fuel. Because of its ease of use, repeatability and accuracy, they also recommend using the IQT test [117] to determine cetane numbers for surrogate components, their mixtures and the target fuel.

Puduppakkam et al. [4] presented an approach where the component type and quantity in a surrogate fuel were determined by matching a number of properties of the target fuel. The proposed properties to be matched in the target fuel were lower heating value, C/H ratio, distillation curve, and ignition quality. Since the target fuel in this case was gasoline, octane number was used as a measure of ignition quality. For diesel, cetane number can be used. The distillation curve is matched by matching the T10, T50 and T90 points, where T10 is the mixture boiling temperature where 10% of the liquid fuel volume is distilled. An iterative approach was used to determine the composition of the surrogate (as shown in Fig. 8).

In the future work on surrogate fuels, many of the above characteristic properties will likely be used to specify surrogates for practical fuels, including NMR to specify chemical composition, C/H ratio to ensure proper flame temperatures, cetane number for ignition quality, threshold sooting index for sooting propensity, and a method for specifying a proper distillation curve. However, these properties are global indicators for an initial selection of a surrogate fuel. Further refinement of the surrogate selection can be made by comparing the surrogate and target fuel behavior in fundamental laboratory devices like shock tubes, flow reactors, jet stirred reactors, rapid compression machines, and premixed and non-premixed flames. For diesel spray properties, constant volume combustion chambers can be used to assess the spray characteristics

of the surrogate and target fuel [91, 118]. Finally, engines that provide optical access to the combustion chamber and allow the application of advanced laser/imaging diagnostics can provide validation data for surrogate fuels in practical combustion devices.

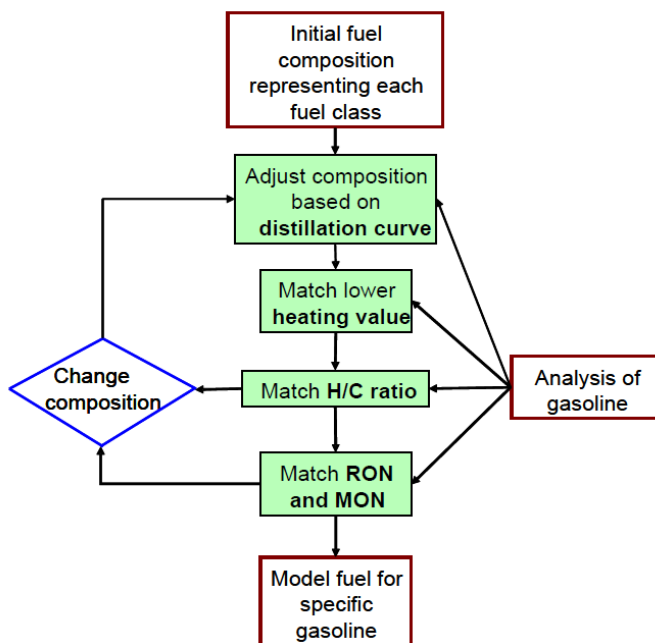
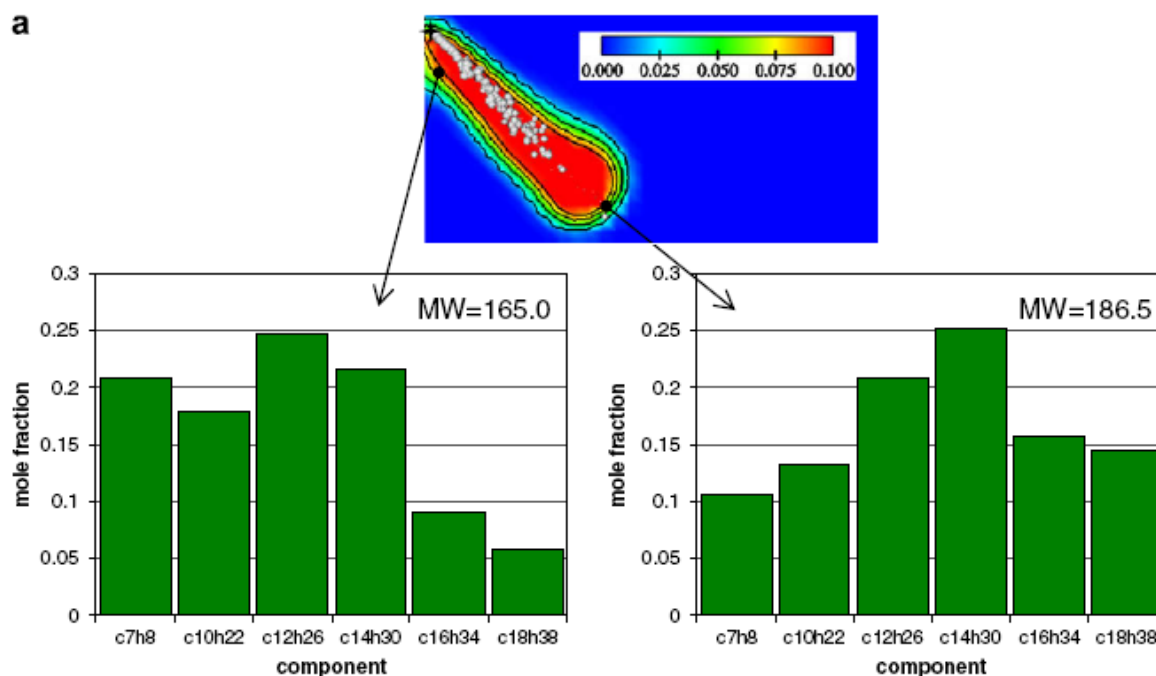


Figure 8. Flow chart for developing model fuels for gasoline [4].

## PHYSICAL PROPERTIES

Physical properties for surrogate components, their mixtures, and target real fuels are needed to simulate combustion of diesel fuel in internal combustion engines. Also when experiments are performed, the physical properties of the diesel surrogate fuel needs to match those of the target fuel so that their injection, vaporization, and mixing characteristics are similar. In a recent paper on a computational fluid dynamic model for diesel combustion [119], the physical properties needed to simulate the diesel spray were density, vapor pressure, surface tension, liquid viscosity and thermal conductivity, heat of vaporization, liquid heat capacity, fuel vapor diffusivity, thermal conductivity and viscosity. This work also showed that it is important to properly treat the vaporization properties of a surrogate diesel fuel. In their simulations using a six-component surrogate for diesel fuel, Ra and Reitz demonstrate that light components are more prevalent in the upstream gases of a diesel spray, while heavy components are more prevalent downstream (Fig. 9). Other physical properties that are needed are transport properties of the species in the gas phase (viscosity, thermal conductivity, species transport). As discussed below, Holley et al. [120] show that the most important species for which accurate gas-phase species transport are needed are the fuel components and the light species (OH, H, O, O<sub>2</sub>, CO<sub>2</sub> and H<sub>2</sub>O), particularly O<sub>2</sub>. Recent progress in improving the knowledge of physical properties of surrogate components, their mixtures and real fuels is discussed below.



**Figure 9. Computed concentration of vaporized hydrocarbons in a surrogate diesel spray from a multi-component vaporization model at 0.5 ms after start of injection [119].**

Holley et al. [120] proposed transport properties for n-alkanes up to tetradecane and 1-alkenes up to dodecene based on correlations of corresponding states [121]. They used these new transport properties to model the propagation and extinction of n-dodecane flames. They were able to quantify the relative importance of chemical kinetics and transport properties on flame propagation and extinction. In this paper and a subsequent paper [122], they identified the critical species for which accurate species transport is needed to accurately calculate flame speeds and extinction. Calculations of laminar flame speed showed a high sensitivity to the diffusion coefficient for  $O_2$  and some sensitivity for H, O and OH. Calculations of flame extinction showed a high sensitivity to the diffusion coefficients of the fuel, OH, H, O,  $O_2$ ,  $CO_2$  and  $H_2O$ .

For liquid fuel properties, Caudwell et al. [123] measured the viscosity and density of five hydrocarbons (octane, decane, 1,3-dimethylbenzene, 1,2,3,4-tetrahydronaphthalene, and 1-methylnaphthalene) over a temperature range of 298 to 473K and a pressure range of 0.1 to 200 MPa. The measurements had relative uncertainties of 2% for viscosity and 0.2% for density. Correlations for density and viscosity were developed and compared to literature data.

Hernández-Galván et al. [124] experimentally measured the liquid viscosity of cyclohexane and mixtures of cyclohexane with tetradecane and benzene over a temperature range of 331 to 393K and a pressure range of 0.7 to 60 MPa. They developed viscosity models that were able to satisfactorily represent the viscosity of the binary systems over the entire pressure, temperature and composition range studied.

Perkins et al. [125] measured the thermal conductivity of methylcyclohexane and propylcyclohexane over a wide range of temperature (300-600K) and pressure (0.1 to 60 MPa). They used the experimental data to develop correlations for thermal conductivity that are estimated to have a relative uncertainty of 4% at a 95% confidence level.

Bruno et al. [126, 127] have developed an approach called the advanced distillation curve (ADC) for measuring distillation curves for practical fuels that measures the true thermodynamic state of the fluid. The technique obtains accurate temperatures, pressures and volumes so that the results can be used for equation of state development for the fuel. Equations of state provide functional relationships of density, pressure, temperature and provide other thermodynamic quantities such as heat capacity. They also use gas chromatography and mass spectrometry to characterize the various distillation fractions of the fuel. Such characterizations are needed to specify the composition of the vapor that evaporates from fuel droplets in diesel combustion simulations and to validate multi-component vaporization models.

Huber et al. [128] developed a surrogate mixture model to represent the physical properties of a coal-derived liquid fuel. They used gas chromatography with mass spectrometry to analyze the composition of the coal-derived fuel. The coal-derived liquid was mainly composed of cyclic alkanes, especially decalins. An advanced distillation curve method was used to obtain the distillation properties of the coal-derived fuel. From the experimental data obtained, they developed a five-component surrogate model (n-propylcyclohexane, trans-decalin, alpha-methyldecalin, bicyclohexane, and n-hexadecane) that was able to predict density, speed of sound and viscosity of the target coal-derived fuel within 1, 4, and 5% respectively of available experimental data. A low and high molecular weight compound was included in the surrogate to properly predict the initial boiling point and the tail of the target distillation curve. Later, they applied the same approach and derived a seven-component surrogate fuel for a Fischer-Tropsch S-8 jet fuel [38]. The seven components were n-nonane, 2,6-dimethyloctane, 3-methyldecane, n-tridecane, n-tetradecane, n-pentadecane and n-hexadecane. These components were selected from a list of components actually measured in the S-8 jet fuel. The amounts of each component were optimized to obtain the best agreement with the experimentally-measured density, viscosity, sound speed and distillation curve of S-8 jet fuel. They found that the overall shape of the distillation curve of the surrogate is determined by only four components. However, small amounts of a low and a high molecular weight n-alkane were added to the surrogate to achieve the desired initial boiling behavior and the proper tail of the end of the distillation curve. The inclusion of branched hydrocarbons was necessary to accurately simulate the thermal conductivity of the target fuel. The approach that Huber et al. have developed also can be applied to matching diesel surrogate fuels to real diesel fuels.

## SUMMARY

Recent advances in the development of surrogate fuels for diesel have been reviewed. For the chemical class of large n-alkanes, there has been considerable progress made on chemical kinetic modeling and experimental investigations. Significant progress has been made in all the fuel classes of iso-alkanes, cycloalkanes and aromatics. However, limited work on the fuel class of tetrahydronaphthalenes (tetralins) could be found in the literature. For reducing the large chemical kinetic models that result from surrogate fuel model development, significant progress has been made on new mechanism reduction methods.

Recommendations for future work have been made. With regard to pure components, fundamental experimental data is needed to fill out the higher carbon range of diesel fuel (C15 to C10). This is difficult to do experimentally because of the high boiling point of these hydrocarbons and computationally because of the large number of species and reactions that are needed. There is a considerable gap in the work on iso-alkane chemical class. The iso-alkanes in diesel fuel are lightly branched with one or two methyl side groups. No fuel component models or experimental measurements of such hydrocarbons in the carbon range of diesel fuel have been made to the author's knowledge. For cycloalkanes, most of the work has been done on the light end of the carbon range of diesel fuel. For work on multi-component surrogate fuels, there is again a lack of work on surrogate fuels that have components to represent the high molecular weight end of diesel fuel. Also, lightly-branched iso-alkanes need to be included in the surrogate mixture.

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